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AN ASSESSMENT OF THE CONCEPT OF CRITICAL TEMPERATURE IN UNDERGROUND POWER CABLE DESIGN

Report No 91-204-K

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ABSTRACT

Three laboratory tests were performed to determine the critical temperature of a uniform sand. In this study, the critical temperature of a soil is defined as the temperature at which an abrupt increase in thermal resistivity takes place. The critical temperature for the sand was inferred from the test results by both direct and indirect methods. The results indicate that the critical temperature is not a unique value, but it is a function of the heater power. This finding raises the question of the validity of using the "Method of Two-Layers of Moisture Potential" for the thermal design of underground power cables in thermally unstable soils without considering the heat flux at the cable soil interface.

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To Dr. D. Mills
Director
Research Division

AN ASSESSMENT OF THE CONCEPT OF CRITICAL TEMPERATURE IN UNDERGROUND POWER CABLE DESIGN

1.0 INTRODUCTION

The performance of underground power cables is critically affected by the thermal properties of backfill soil around the cable/1,2/. Heat generated by an underground power cable has to be dissipated through the surrounding soil. The temperature gradients imposed on the soil by the heat dissipation process, may induce moisture migration away from the cable/3,4/. The thermal resistivity of the soil, being strongly dependent on its moisture content, increases with continuous depletion of moisture around the power cable. This can result in cable temperatures exceeding its safe operating limit.

The possibility of thermal drying of soil around a power cable complicates the thermal design process. Because of the coupling effect between the thermal gradients and the soil moisture, close form solutions are not possible. One of the design methods used by the cable engineers in Europe to account for soil thermal drying is the "Method of Two-Layers of Moisture Potential"/5,6/. This design method is based on the following assumptions: I) The soil in its initial moisture state will have a uniform thermal resistivity, and when the cable surface temperature exceeds a certain critical limit, the soil will start to dry out, resulting in a zone with higher but uniform thermal resistivity. II) The development of such a dry out zone does not change the shape of the original isothermal pattern, even though the numerical values of the isotherms within the dry out zone may

change. III) At steady state, the outer boundary of the dry out zone is coincident with the critical temperature isotherm.

According to this design method, the cable ampacity is a function of the critical temperature of the backfill soil. At present, this approach is used in the thermal design of cables carrying continuous load, and the critical temperature values are assumed to be unique to a given soil type. In this study, a laboratory scale experiment was designed and conducted to determine the critical temperature of a uniform sand.

2.0 THE EXPERIMENT

The test layout in a 900 mm x 900 mm x 600 mm wooden box is shown in Figure 1. The wooden box was thermally insulated with 50 mm thick SM styrofoam board glued to its exterior walls. The interior walls of the box were hydraulically sealed with a moisture sealant paint. The top of the box, which was not thermally insulated was moisture sealed with a PVC sheet.

A 38 mm diameter by 600 mm long heater manufactured by Geotherm Inc. was used to simulate the heat generation from an underground power cable (Figure 2). The heater power was controlled by a power supply shown in Figure 3. By controlling the electrical current supply, a constant heat energy was generated by the heater. To ensure the continuity of the tests, an uninterruptable power supply was used between the wall outlet, and the hardware of the experiment.

The temperature regime in a plane perpendicular to the heater was monitored by an array of thermocouples. The predetermined spacings between thermocouples were ensured by glueing thermocouples onto a high thermal resistivity PVC rod to form a thermocouple tree, Figure 4. Three thermocouple trees, AA', BB', and CC' shown in Figure 5, were used to monitor the thermal regime. All the thermocouples were monitored by a HP data

logger connected to a desktop computer (Figure 3). The recorded data was stored on floppy disks for further analysis. The real time temperature plots were displayed on the computer monitor to provide updated information on the status of each test.

Thermal needles were installed at critical locations paralleling the heater to determine the thermal resistivity of the sand as the test progressed (Figure 2). The moisture contents of the sand adjacent to the thermal needles were inferred from the relationship between moisture content and the thermal resistivity for the sand. Three thermal needles were used in test #1, and 4 thermal needles were used in tests #2 and 3. The thermal needles used were manufactured by Geotherm Inc.. Each needle was 3 mm in diameter and 100 mm long (Figure 2). A type "T" thermocouple was used to monitor the temperature change within the needle. The locations and spacings of the thermal needles were unique for each test and their locations for the 3 tests performed are listed in Table I. The spacings between the thermal needles increased with the increase in heater power used in the test. This strategy of locating the thermal needles ensured the capturing of the movement of the drying front during a test.

3.0 TEST PROGRAM

Three tests were carried out with heater power of 98.5, 65.5, and 32.8 w/m. The uniform silica sand used for these tests had a grain size finer than 1.0 mm and coarser than 0.5 mm. The relationship between the thermal resistivity and moisture content for this sand as determined by TPA is shown in Figure 6. The sand was mixed thoroughly in a rotary mixer to a uniform moisture content value of 3% and it was then packed into the sandbox in 50 mm lifts to a dry density of 1681 +/- 5 kg/m^3.

The vertical thermocouple tree BB' beneath the heater was installed in place prior to the placement of the sand. When the sand reached the heater level, the heater was put in place by inserting the ends of the heater into the guides located on the walls of the

sandbox. Thermal needles were then installed at designated locations parallel to the heater (Table I). The thermocouple trees AA', and CC' were positioned and the sandbox was packed in lifts to the top. To ensure uniformity of the initial moisture content of the sand, the compacted sand was allowed to sit in the sandbox for 2 days prior to the starting of the heater.

In this study, three tests were performed at 3 different heater powers of 98.5, 65.5, and 32.8 w/m. The sand temperature were continuously monitored with three thermocouple trees. Thermal resistivity of the sand at different locations were monitored daily to determine the advance of the thermal drying front.

At the end of each test, soil samples were obtained to determine the final moisture distribution in the sand. The sampling sections were adjacent to the thermocouple trees AA', BB', and CC' as shown in Figure 5. Along sections BB' and CC', continuous samples were obtained by using a 25.4 mm diameter steel tube. Each sampling hole was protected from caving with a 100 mm diameter steel casing. After the completion of sampling along section CC', the sand above the heater level was excavated. Scoop samples were obtained along section AA' as the sand was excavated.

4.0 RESULTS AND DISCUSSION

In all of the three tests, an abrupt change in the thermal resistivity profile occurred, which is a characteristic of the thermal drying front. A typical photograph of the dry out zone is presented in Figure 4. The soil temperature at which an abrupt increase in thermal resistivity takes place is termed as the Critical Temperature. For each test, the critical temperature of the sand was determined by two methods: 1) the direct method, and 2) the indirect method.

In the direct method, the final temperature, and moisture content profiles along thermocouple trees AA', BB', and CC' (Figure 5) were used to determine the location of the dry out boundary and the corresponding temperature, was inferred as the critical temperature.

In the indirect method, the data obtained by thermal needles were used to determine the critical temperature. Each thermal needle measurement gave both temperature and thermal resistivity of its location. The critical temperature was determined by plotting the temperature versus thermal resistivity value, as shown in Figure 7.

The critical temperatures inferred by the above two methods showed good agreement as shown in Table II.

The results of Test #1 with a heater power of 98.5 W/m are summarized in Figures 7, 8, and 9. Figure 7 shows a plot of the thermal resistivity of sand as measured by thermal needles 1, 2, and 3 (Figure 5) versus the sand temperature at their corresponding locations. An abrupt increase in the thermal resistivity value from about 60°C-cm/w to about 230°C-cm/w occurred at the critical soil temperature of 48°C.

Figure 8 which show the final moisture content profile along sections AA', BB', and CC' confirms the soil thermal drying within a radial zone of about 90 mm from the centre of the heater. The final temperature profiles plotted in Figure 9 also show a deviation from the exponential relationship, at a location of about 80 to 100 mm from the centre of the heater. Thus both moisture, and temperature profiles indicate the drying front to be located at 80 to 100 mm from the centre of the heater where the soil temperature was close to the critical temperature of 48°C.

Similar observations were made for tests #2, and #3 which were conducted at heater powers of 65.5 w/m, and 32.8 w/m respectively. The results of these two tests are summarized in Figures 10 to 15.

From Figures 10 and 13, the critical temperatures corresponding to the heater powers of 65.5 w/m, and 32.8 w/m are inferred to be 40°C, and 33°C respectively. The temperature and moisture content profiles (Figures 11, 12, 14 and 15) recorded at the end of these tests, near steady state condition, confirm the presence of a dry out zone.

A summary of the critical temperature data determined from this study is presented in Table II. This data shows that a good correlation exists between the critical temperature values obtained from direct and indirect methods. In Figure 16, the critical temperature values are plotted as a function of the heater power. This figure shows that the critical temperature of the uniform sand is not a unique value but it is a function of the heater power. This finding raises the question of the validity of using the two-layer model for the thermal design of underground power cables in thermally unstable soils without considering the heat flux at the cable soil interface.

Gazzana-Priaroggia/5/, who proposed a two-layer model demonstrated the impact of critical temperature on underground power cable design by considering a typical cable installation (Appendix A). In their example, a single cable was considered. The wet and dry thermal resistivity of the backfill soil were 1.05 and 2.5°C.m/w, respectively. The results of their calculations are presented in Table III. A change in critical temperature from 30°C to 50°C increases the permissible ampacity of the cable from 412 to 580 A. This is a significant increase of 40% in ampacity of the cable system. This example shows that the permissible ampacity calculations based on the two-layer model, are very sensitive to the critical temperature value, which is shown to be strongly dependent of heat flux. Thus the inherent assumption in the two-layer model that a single value of critical temperature is applicable for a given soil type is questionable.

5.0 CONCLUSION

In this study the critical temperature values for a uniform sand were determined by a specially designed scale model experiment. It is shown that the critical temperature in sand is a function of the heater power. This finding raises questions about the applicability of the two-layer model for the design of underground power cables in thermally unstable soils. It is proposed that critical temperature values of various typical cable backfills are determined as a function of heat flux so as to modify the application of the two-layer model for underground power cable design.

ACKNOWLEDGEMENTS

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	Distance from Centre of Heater, mm			
	No. 1	No. 2	No. 3	No. 4
Test #1	49	79	289	--
Test #2	49	79	109	289
Test #3	49	89	169	239

Table I Locations of thermal needles.

	Heater Power w/m	Critical Temperature, °c			
		Indirect Method	Direct Method		
			section AA'	Section BB'	Section CC'
Test #1	98.5	48	47	48	46
Test #2	65.5	40	36	37	36
Test #3	32.8	33	32	32	32

Table II Summary of test results.

Echauffement critique $\Delta\theta_c$ *Critical temperature rise* $\Delta\theta_c$ K	Température critique θ_c *Critical temperature* θ_c °C	Courant pour θ_c = 85 °C *Current for* θ_c = 85 °C A	Température de la surface du câble *pour* θ_c = 85 °C *Cable surface temperature for* θ_c = 85 ° °C	Courants permettant d'éviter l'assèchement $\Delta\theta'_c = \Delta\theta_c$ *Currents to avoid drying* $\Delta\theta'_c = \Delta\theta_c$ A
0	10	453	—	—
10	20	498	72,4	—
20	30	539	70,4	412
30	40	577	68,4	507
40	50	613	66,4	580
50	60	647	64,4	639
53,7	63,7	659	63,7	659

Table III Results of analysis/5/.

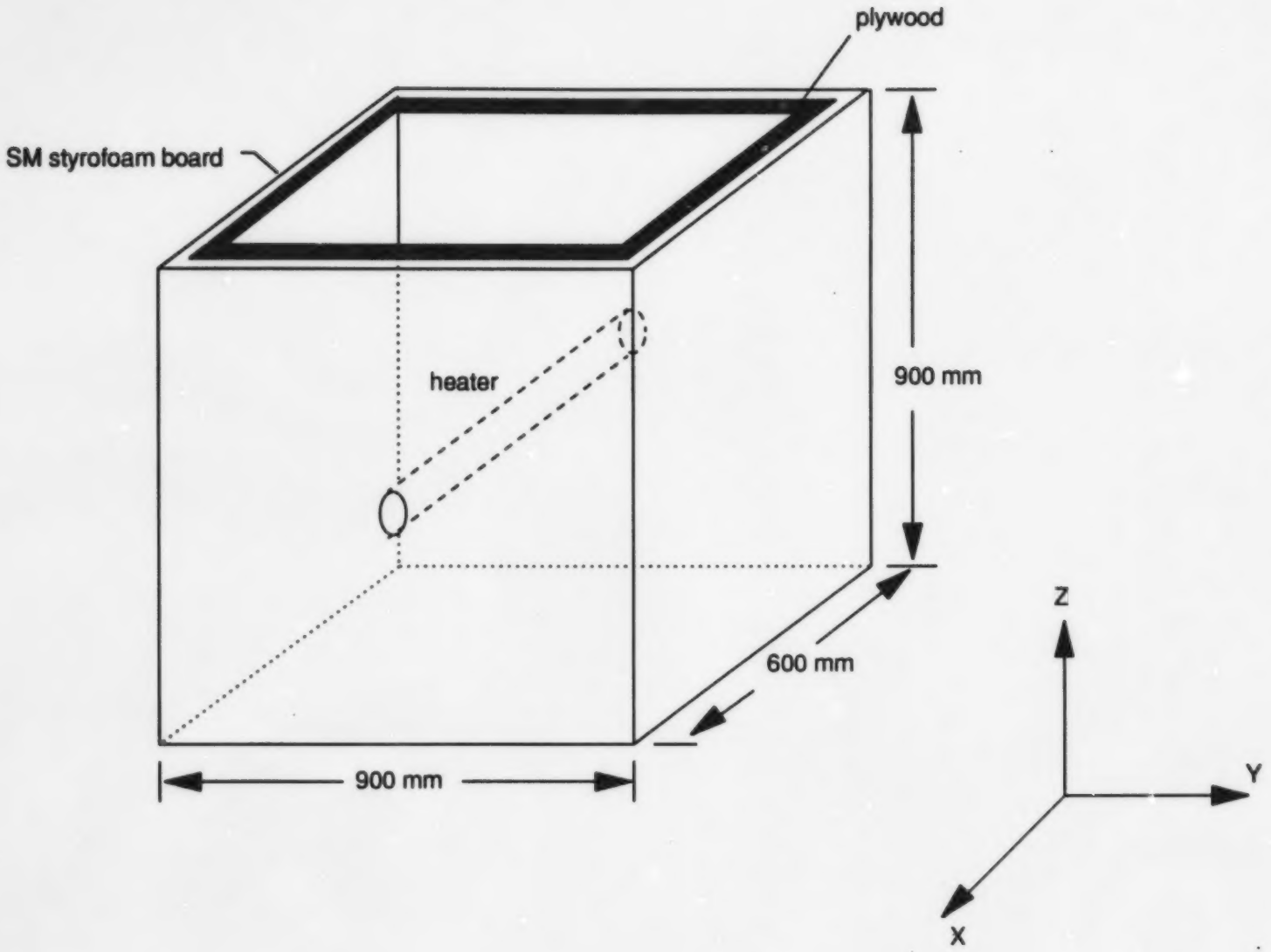

Figure 1 Layout of the sandbox.

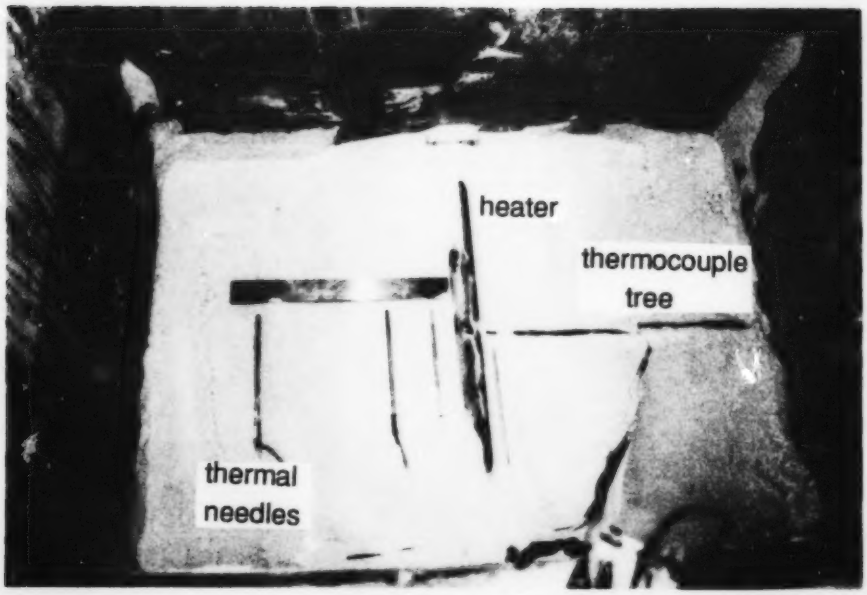

Figure 2 Setup of the sandbox experiment.

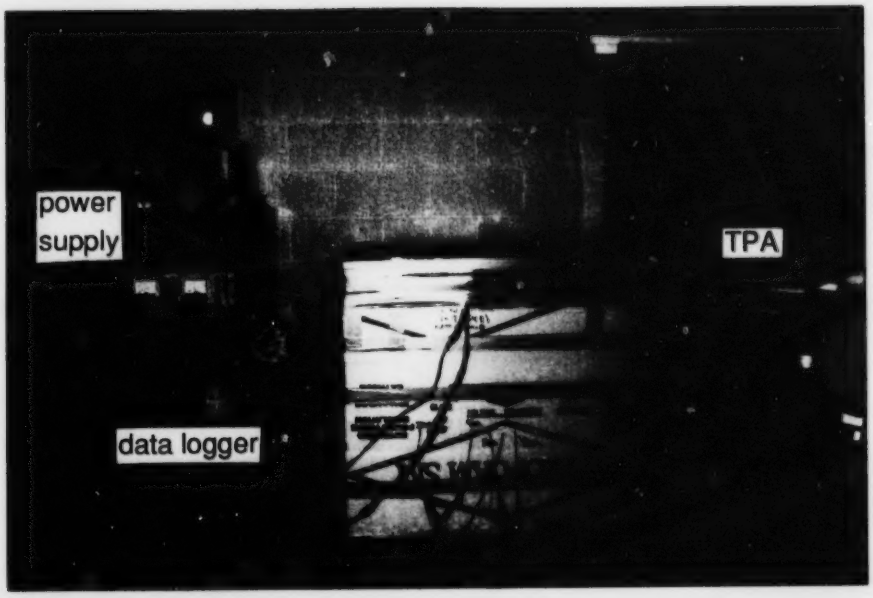

Figure 3 The sandbox, and the monitoring equipments.

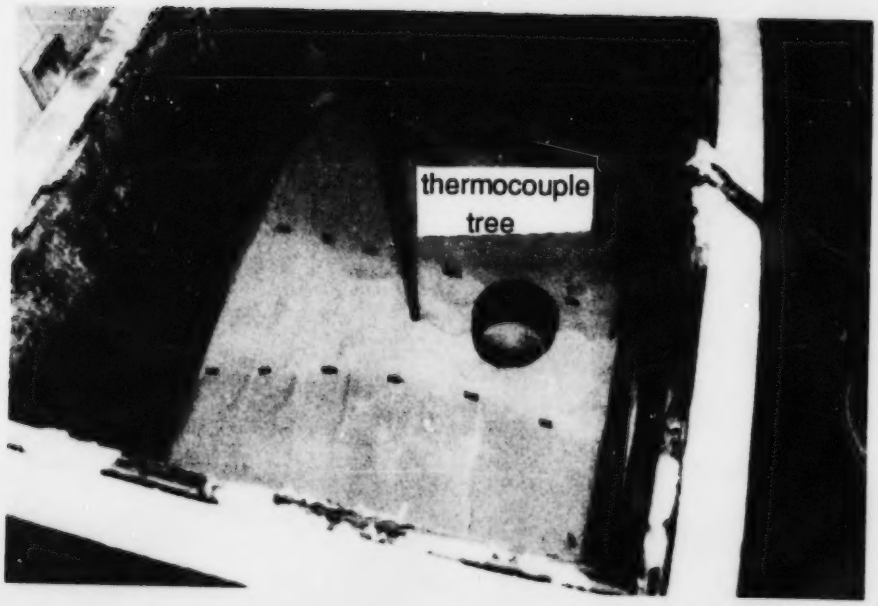

Figure 4 A typical dry out zone.

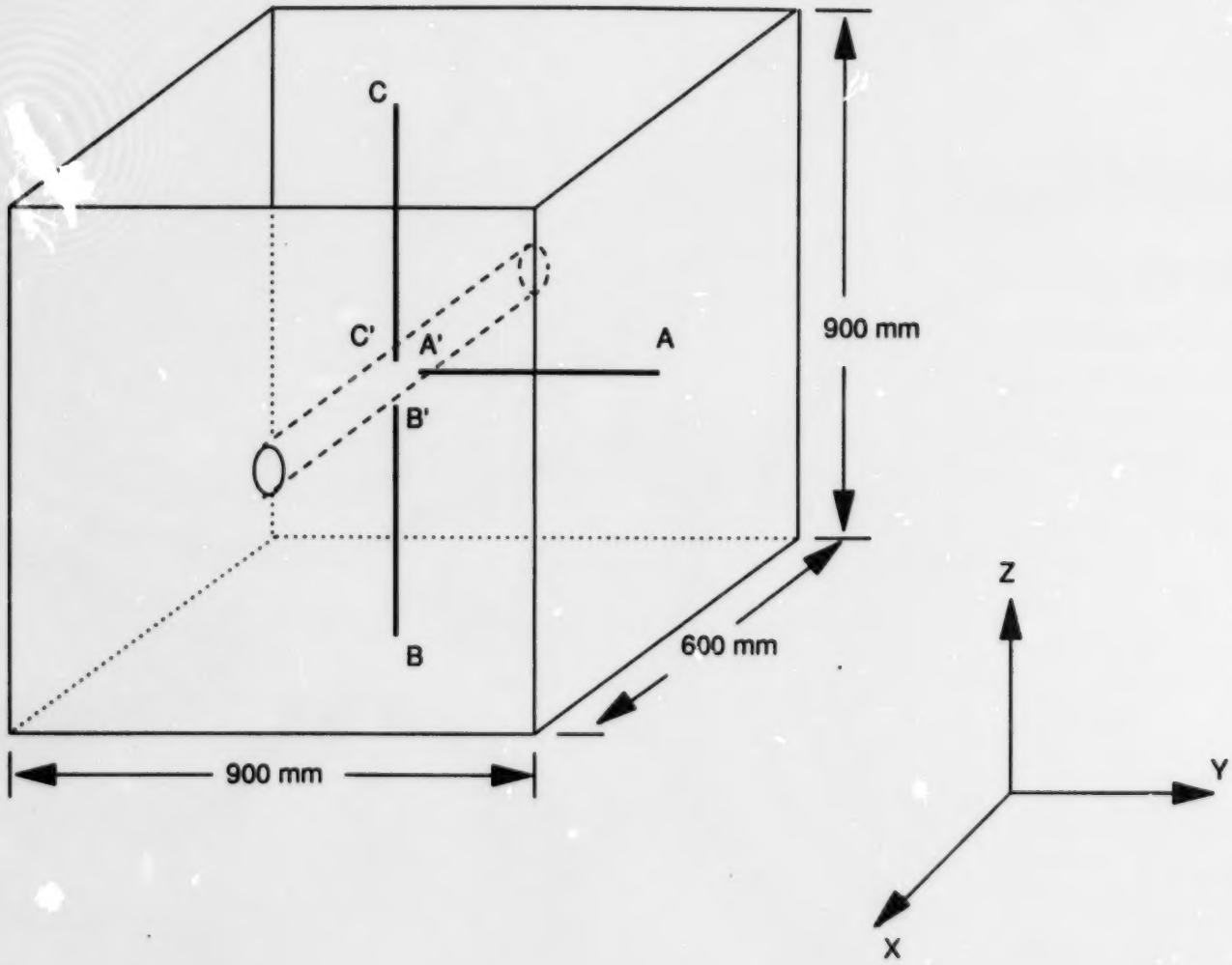

Figure 5 Locations of the thermocouple trees.

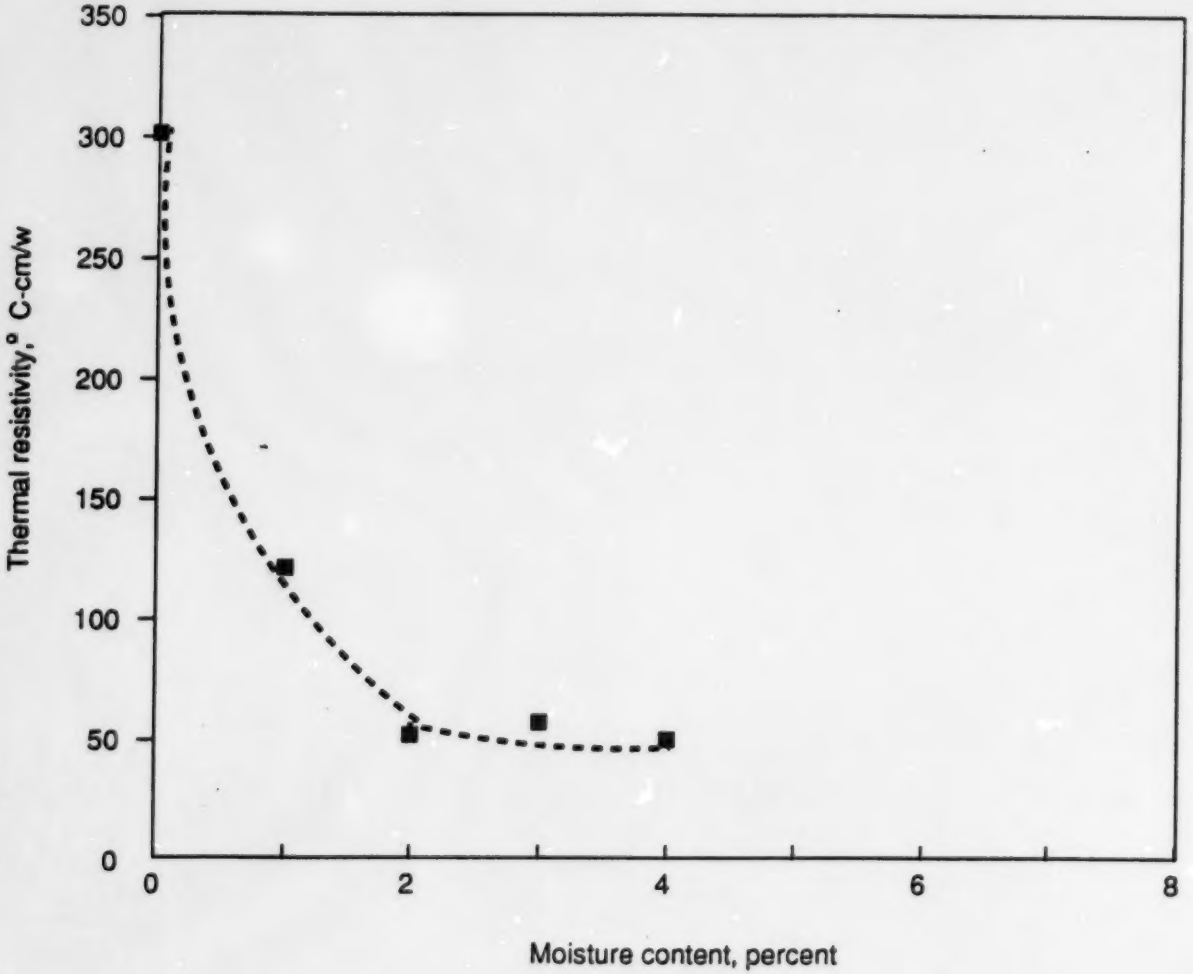

Figure 6 Thermal resistivity versus moisture content of the uniform sand.

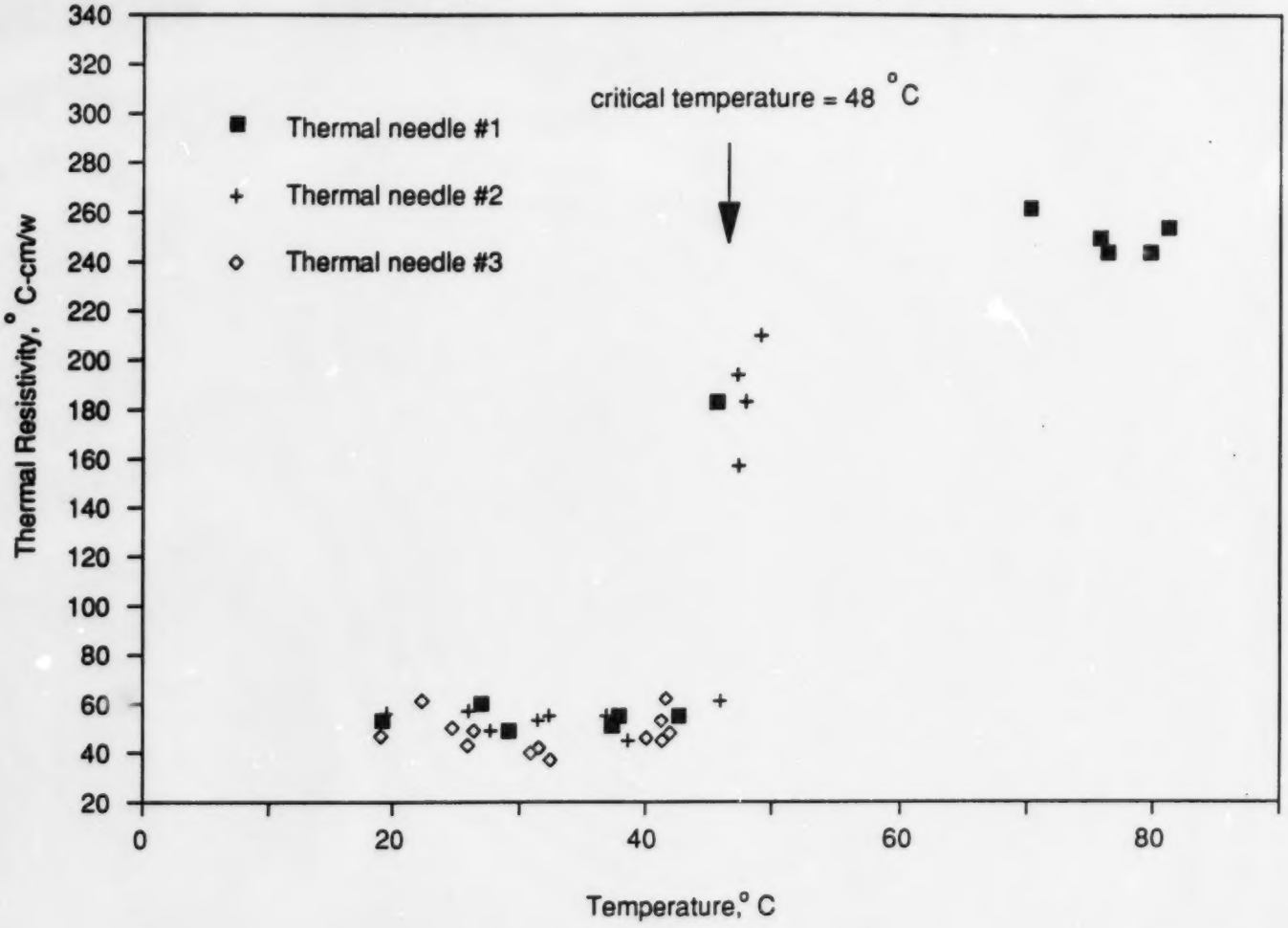

Figure 7 Thermal resistivity versus temperature results determined by thermal needles - Test #1.

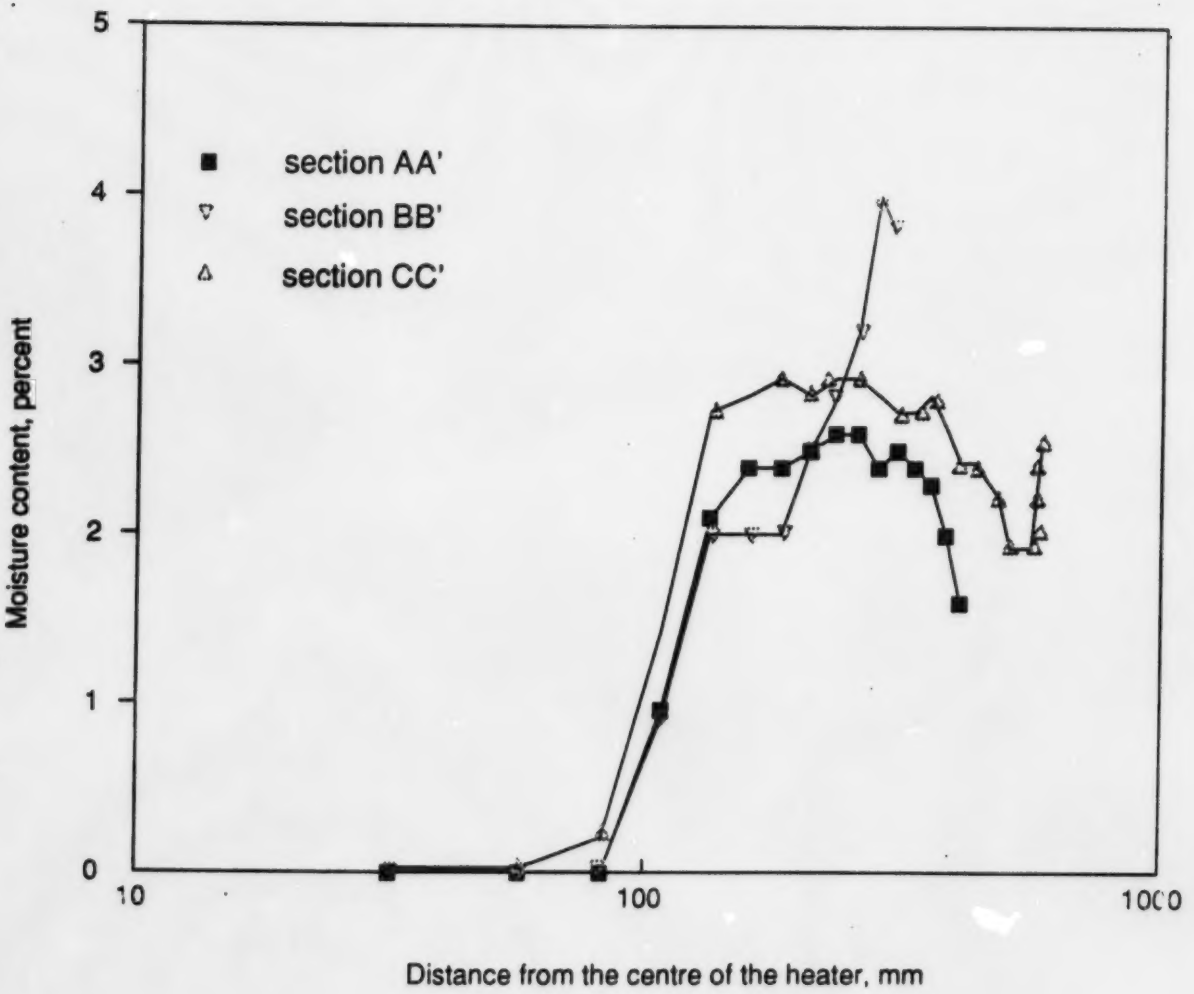

Figure 8 Final moisture content profiles - test #1.

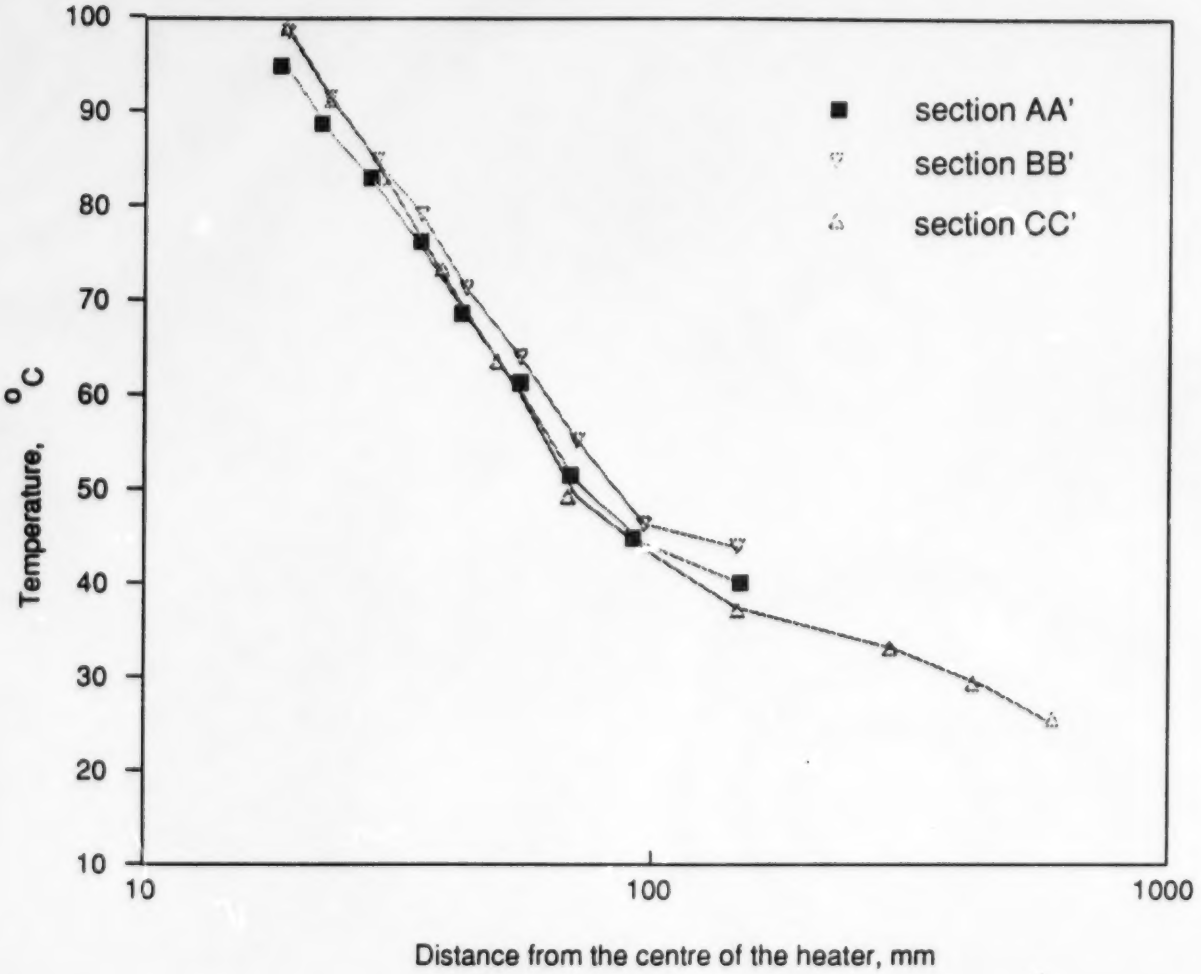

Figure 9 Final temperature profiles - test #1.

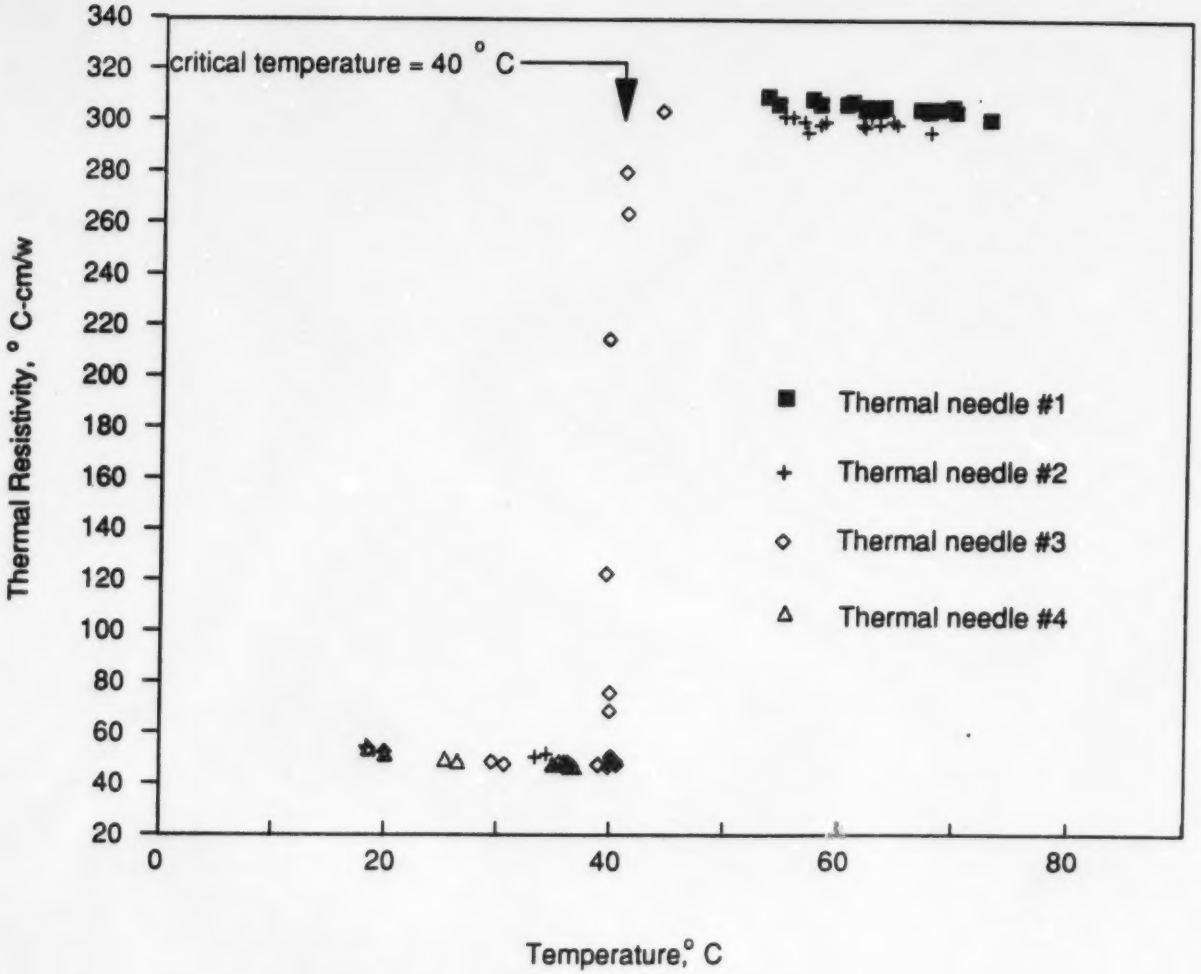

Figure 10 Thermal resistivity versus temperature results determined by thermal needles - Test #2.

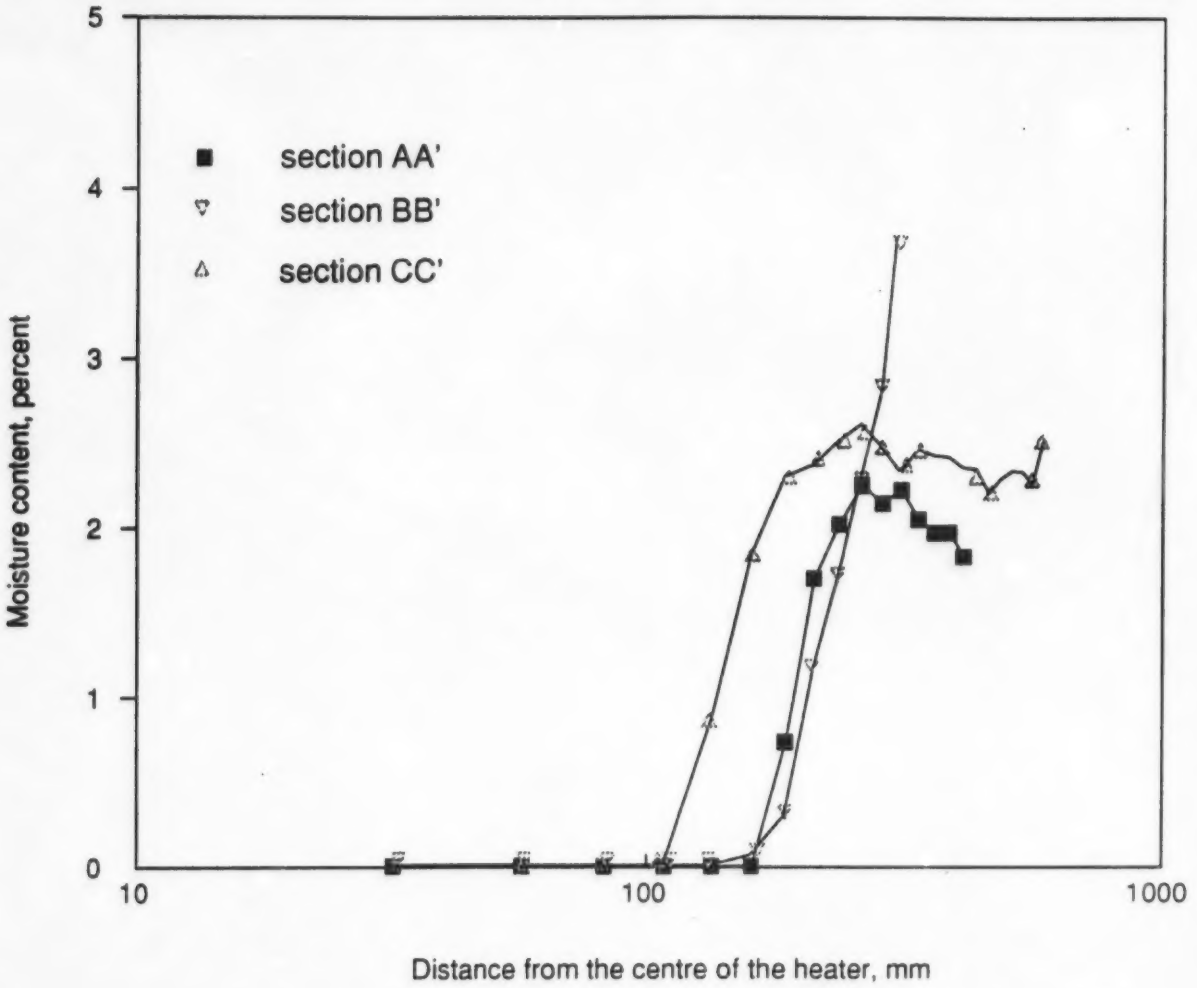

Figure 11 Final moisture content profiles - test #2.

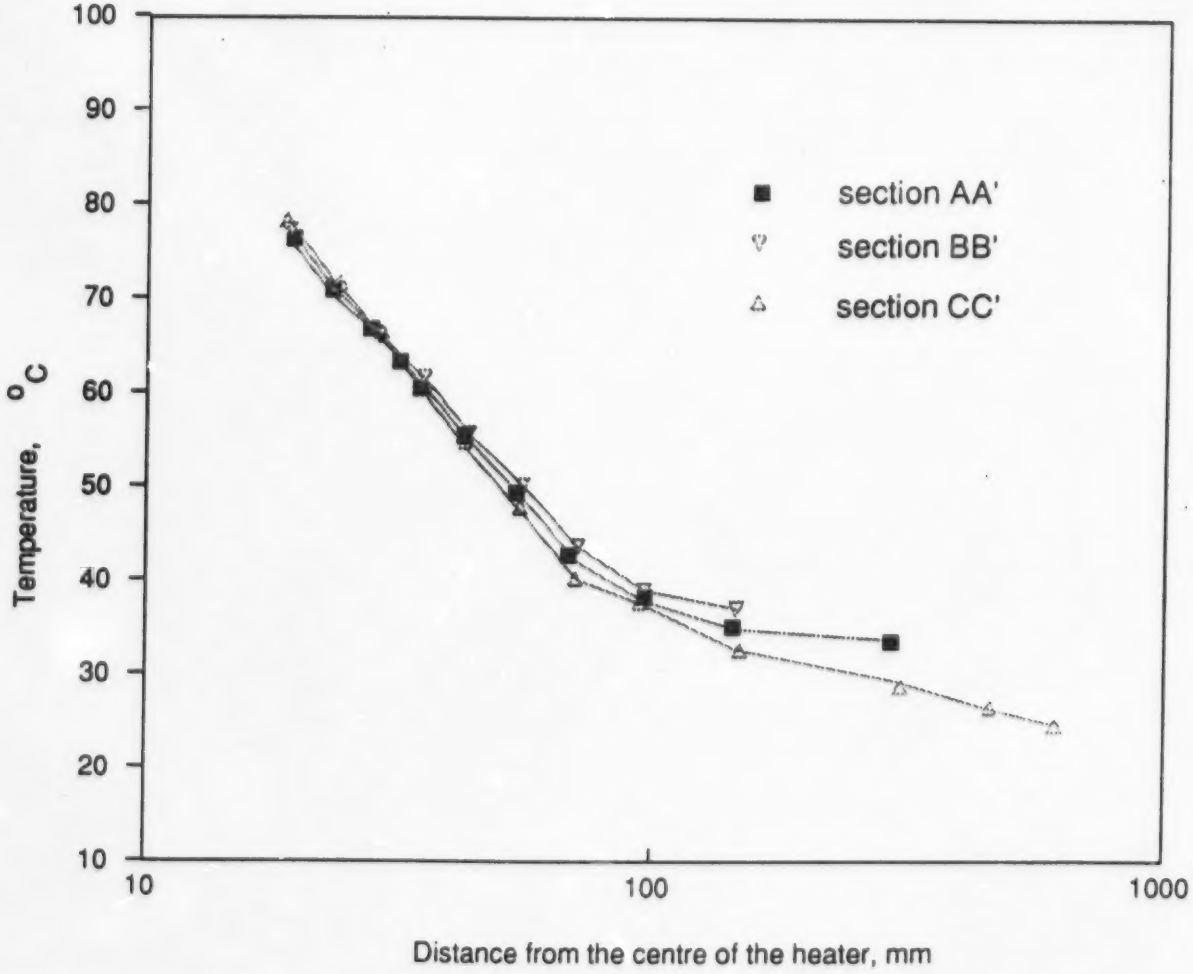

Figure 12 Final temperature profiles - test #2.

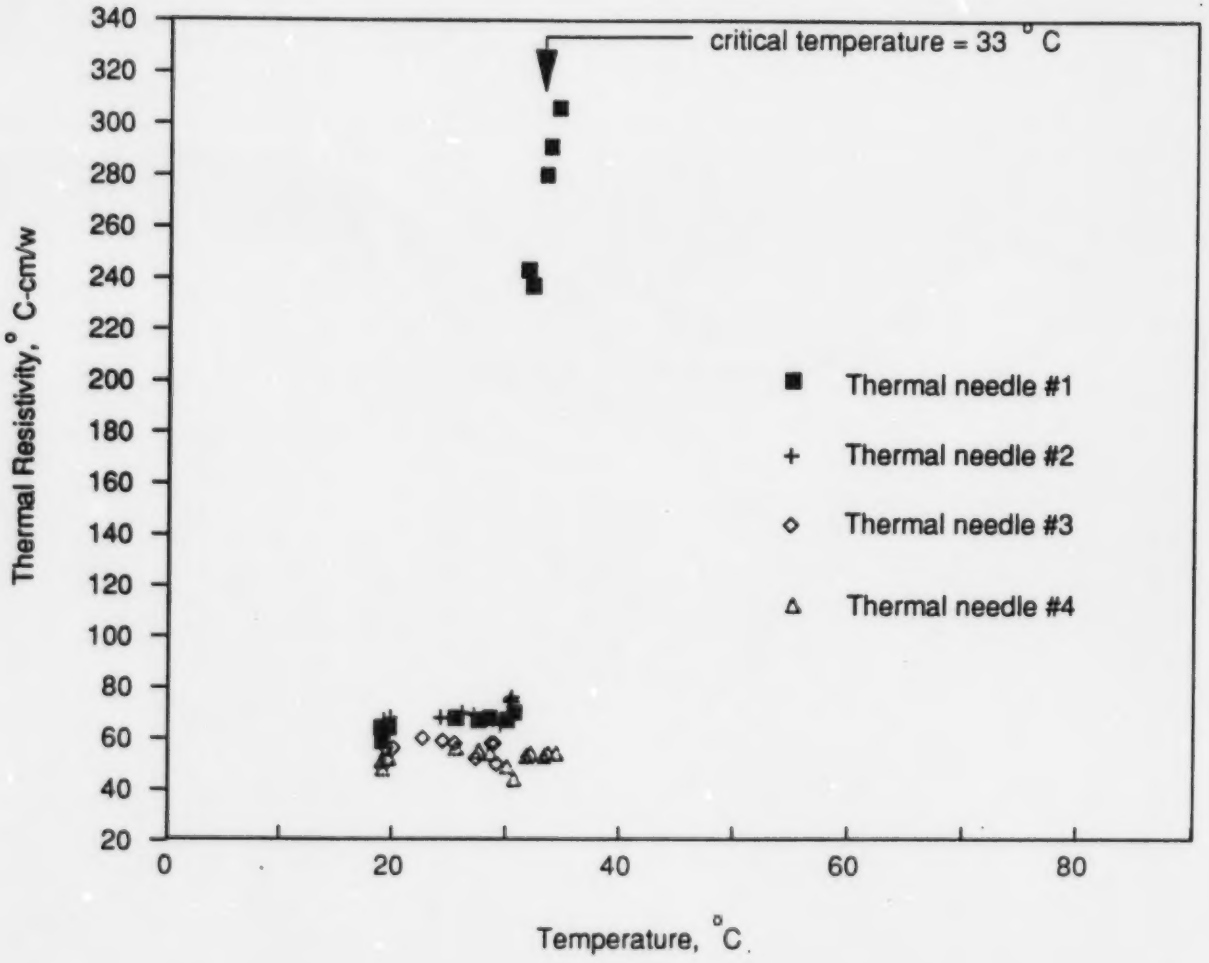

Figure 13 Thermal resistivity versus temperature results determined by thermal needles - Test #3.

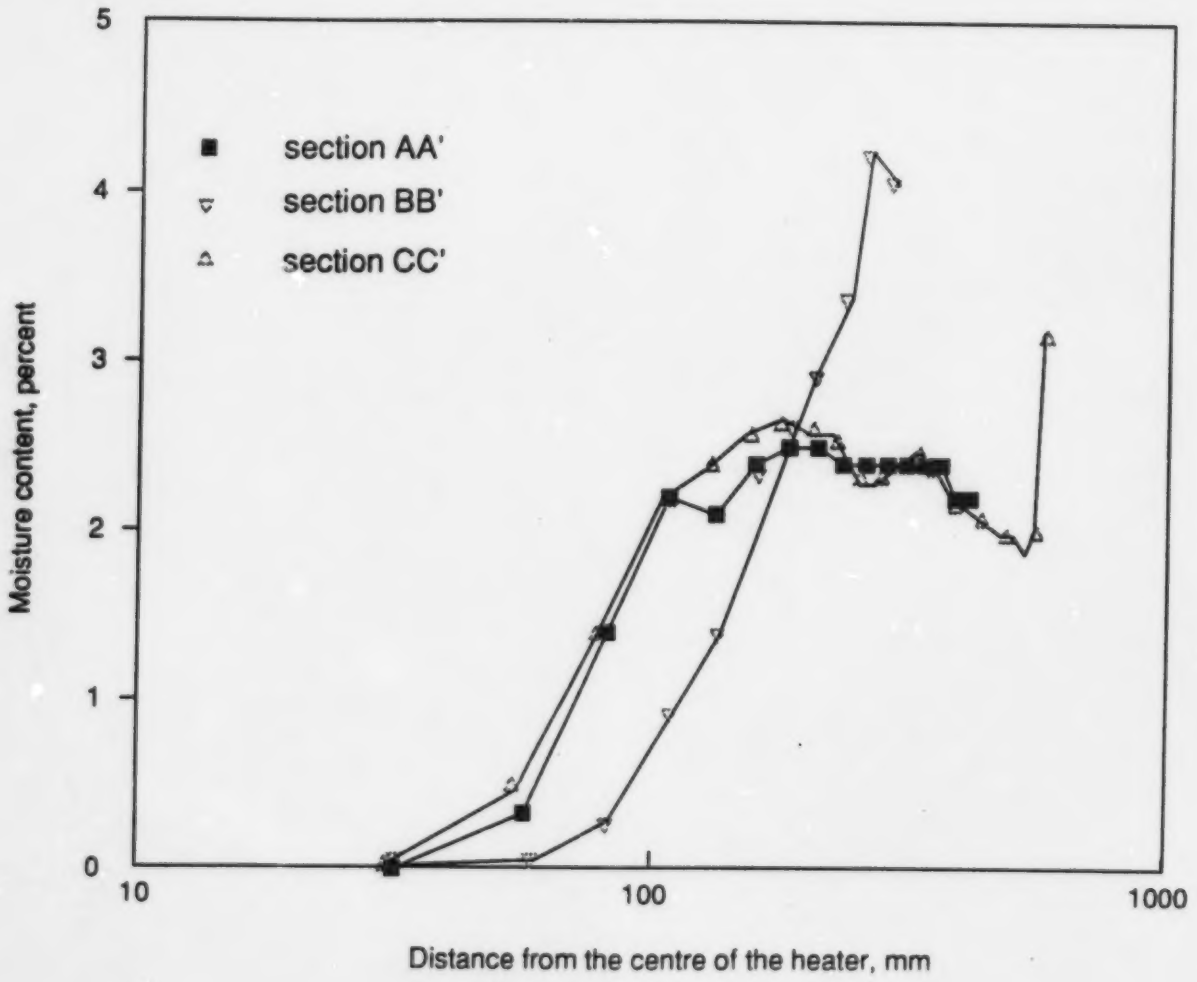

Figure 14 Final moisture content profiles - test #3.

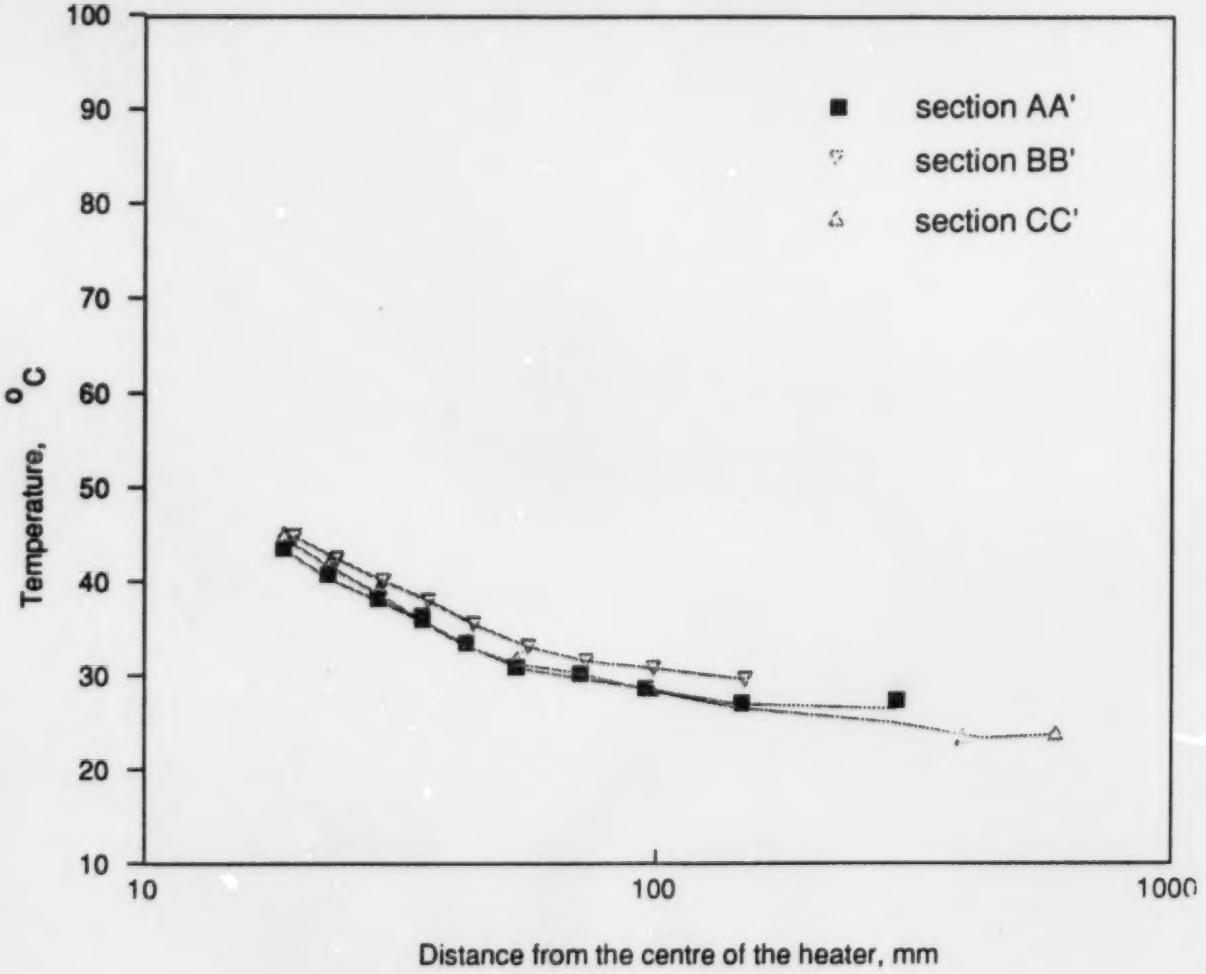

Figure 15 Final temperature profiles - test #3.

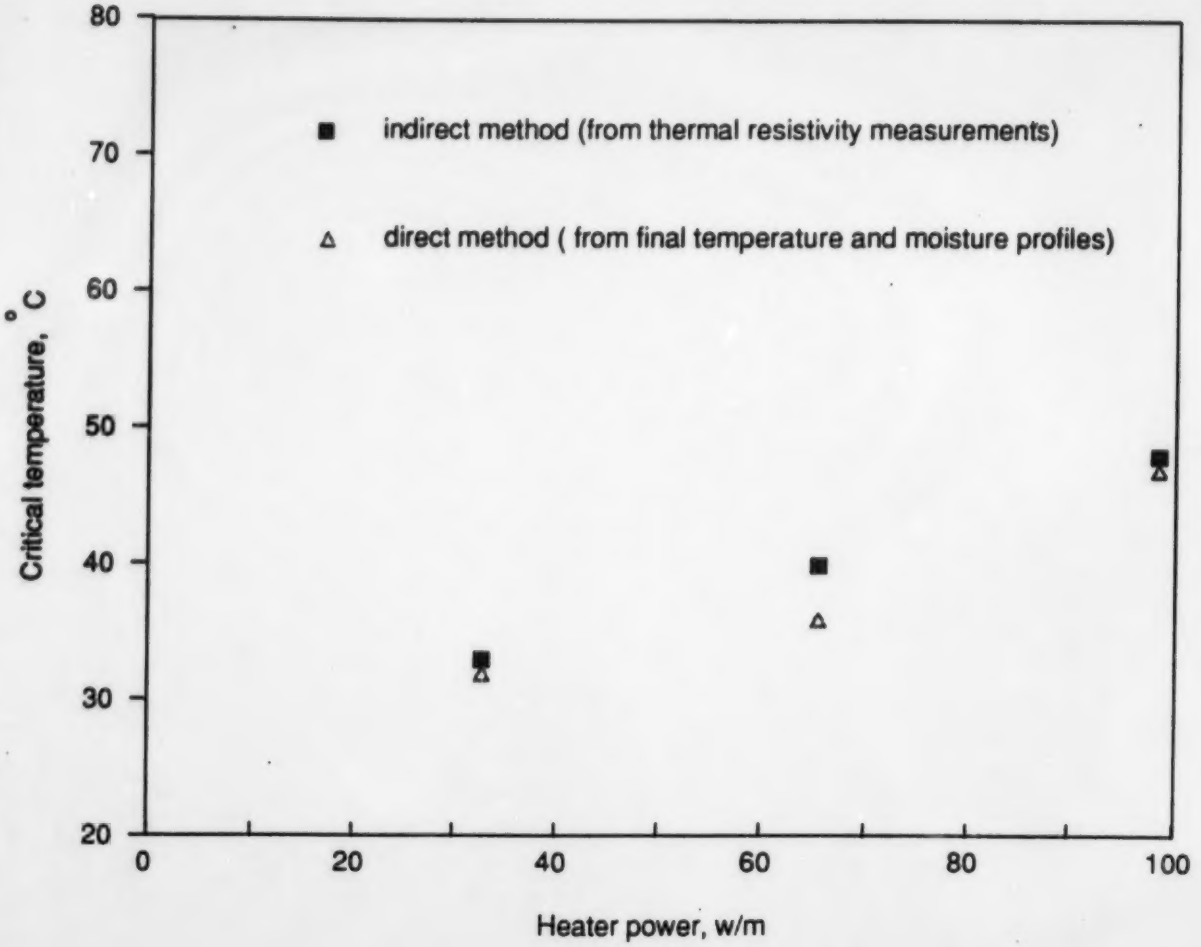

Figure 16 The relationship between critical temperature and heater power.

Appendix I

Cable Design Example.

6. EXEMPLES

6.1. Câble multipolaire, posé directement dans le sol

Données relatives à l'installation

Trois conducteurs 400 mm² cuivre, 132 kV, à l'huile fluide, sous gaine de plomb et gaine PVC.

D_e = 109 mm
L = 1 000 mm
θ_a = 10 °C
θ_c = 85 °C
T_4 (ρ_1 = 1,05 K · m/W) = 0,602 K · m/W
R = 61,2 × 10^{-6} ohm/m à 85 °C
W_d = 1,69 W/m par conducteur
T_1 = 0,487 K · m/W
T_3 = 0,09 K · m/W
λ_1 = 0,0557.

Supposons que le sol sec ait une résistivité ρ_2 = 2,5 K · m/W, de sorte que ν = 2,5/1,05 = 2,381 et (ν − 1) = 1,381.

Les résultats suivants s'obtiennent à partir des équations (5) et (9).

6. EXAMPLES

6.1. Multi-core Cable, Laid Direct

Installation Data

3 core 400 mm² copper, 132 kV, O.F. lead sheathed, PVC served.

D_e = 109 mm
L = 1 000 mm
θ_a = 10 °C
θ_c = 85 °C
T_4 (ρ_1 = 1.05 K · m/W) = 0.602 K · m/W
R = 61.2 × 10^{-6} ohm/m at 85 °C
W_d = 1.69 W/m per core
T_1 = 0.487 K · m/W
T_3 = 0.09 K · m/W
λ_1 = 0.0557.

Assume that the soil when dry has a resistivity ρ_2 = 2.5 K · m/W so that ν = 2.5/1.05 = 2.381 and (ν − 1) = 1.381.

The following results are obtained by the use of Equations (5) and (9).

Echauffement critique $\Delta\theta_c$ *Critical temperature rise* $\Delta\theta_c$ K	Température critique θ_c *Critical temperature* θ_c °C	Courant pour θ_c = 85 °C *Current for* θ_c = 85 °C A	Température de la surface du câble pour θ_c = 85 °C *Cable surface temperature for* θ_c = 85 °C	Courants permettant d'éviter l'assèchement $\Delta\theta_s = \Delta\theta_c$ *Currents to avoid drying* $\Delta\theta_s = \Delta\theta_c$ A
0	10	453	—	—
10	20	498	72,4	—
20	30	539	70,4	412
30	40	577	68,4	507
40	50	613	66,4	580
50	60	647	64,4	639
53,7	63,7	659	63,7	659

La première ligne du tableau correspond à une situation où le sol est asséché en totalité. La dernière ligne correspond au cas où la température critique est supérieure ou égale à la température de surface du câble, c'est-à-dire au cas où il ne se produit donc aucun assèchement.

Si :

$$W < \frac{\Delta\theta_c}{T_4},$$

il ne se produit aucun assèchement.

La dernière colonne donne les courants maximaux de charge admissibles dans le cas où toute migration d'humidité doit être évitée.

The first line in the Table corresponds to a situation where all the soil has dried out. The last line relates to a case where the critical temperature is equal to or greater than the cable surface temperature, i.e. there is no drying out.

If :

$$W < \frac{\Delta\theta_c}{T_4},$$

then no drying will occur.

The last column gives the maximum load currents permitted if moisture migration is to be avoided.